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INTERSTELLAR SCATTERING AND THE SIZES OF ASTRONOMICAL MASERS*

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ABSTRACT

We explore the suggestion that scattering by inhomogeneities in the distribution of electrons causes astronomical masers to appear larger than their actual sizes. It is shown that neither scattering near the source nor scattering in the intervening medium is sufficiently strong to produce this effect.

I. INTRODUCTION

It is necessary to know the actual sizes of OH (18 cm) and H_2O (1.3 cm) maser sources before one can understand the physical processes taking place in them. Burke *et al.* (1968, 1970, 1971), Moran *et al.* (1968, 1971), and Johnston *et al.* (1971) have used very long baseline interferometry (VLBI) to map out a number of OH and H_2O maser sources. They found that the typical source contains 10 or so smaller components. The size of the smallest component of a number of these sources is given in table 1. It is possible that these sizes inferred from VLBI are not accurate indications of the true sizes of the masing regions, and indeed the "size" of such a system is not well defined. The angular size θ_{obs} inferred from a VLBI measurement of a source at distance L is the range of angles over which a spatially incoherent wave front is observed from the direction of the source. The corresponding linear size $L\theta_{obs}$ may be smaller than the true size R of the region which produces the bulk of the observed energy if radiation from a small region is being amplified coherently in passing through a larger region, as would be the case if one were observing a small "hot spot" of unsaturated amplification at the center of a larger saturated region (Litvak 1971). In such a case θ_{obs} is a measure of the size of the smaller region.

On the other hand, scattering of the maser radiation by inhomogeneities in the electron density near the source or in the interstellar medium could distort the wave front and make θ_{obs} appear larger than in the absence of such scattering. It is this latter process which we discuss here. It will be noted from table 1 that (1) the OH source in W49 A has an apparent size of 700 a.u., which is 175 times larger than the water vapor source whose size is 4 a.u., and (2) the angular sizes of the OH sources increase roughly with distance. These observations led Burke *et al.* (1968), Johnston *et al.* (1971), and Litvak (1971) to hypothesize that the observed sizes are attributable to this scattering process, with the sources actually being considerably smaller than θ_{obs}. Since this type of scattering is proportional to λ^2 (see, e.g., Scheuer 1968), one would expect the OH sources to appear larger than the H_2O sources, as observed. In this paper we shall show that simple scattering models cannot account for the observed sizes, and hence the best interpretation is that the actual sizes are comparable with or greater than the observed sizes.

II. SCATTERING IN THE INTERSTELLAR MEDIUM

The theory of radio wave scattering by an inhomogeneous plasma is well known (Salpeter 1967). The theory predicts that radiation of wavelength λ from a point source will

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TABLE 1

OBSERVATIONAL DATA AND THEORETICAL SIZE DUE TO INTERSTELLAR SCATTERING FOR A NUMBER OF MASER SOURCES

		OH SOURCES			H_2O SOURCES		
SOURCE	DISTANCE (kpc)	Angular Size of Smallest Component* (arc sec)	Linear Size of Smallest Component (a.u.)	θ_{scat} (arc sec)	Angular Size of Smallest Component (arc sec)	Linear Size of Smallest Component (a.u.)	θ_{scat} (arc sec)
Orion A.....	0.5	...	...	1.3×10^{-4}	3×10^{-3}(2)	1.5	7.3×10^{-7}
NGC 6334...	0.7	$<1.5\times10^{-2}$(1)	< 10	1.6×10^{-4}	...	...	9.0×10^{-7}
W3.........	2.6	4×10^{-3}(1)	10	3.0×10^{-4}	$<1\times10^{-2}$(3)	<24	1.7×10^{-6}
W24........	10	9×10^{-2}(1)	900	5.9×10^{-4}	...	...	3.3×10^{-6}
W49A.......	14	5×10^{-2}(1)	700	7.0×10^{-4}	3×10^{-4}(4)	4	3.9×10^{-6}

* Numbers in parentheses refer to the following observations: (1) Burke *et al.* (1968); (2) Moran *et al.* (1971); (3) Burke *et al.* (1970); (4) Burke *et al.* (1971).

be scattered into a cone of rms scattering angle θ_{scat} given by (Scheuer 1968)

$$\theta_{scat} = \frac{1}{2\pi}\Delta n\lambda^2 r_e(L/a)^{1/2}\,, \tag{1}$$

where a is the linear scale size of the inhomogeneities, Δn is the rms fluctuation in electron density averaged over a region of volume a^3, r_e is the classical electron radius, and L is the thickness of the scattering medium, usually taken to be the distance from the source to the observer.

The parameters of the interstellar medium enter equation (1) in the ratio $\Delta n/\sqrt{a}$, and Harris, Zeissig, and Lovelace (1970) and Lang (1971) show that this ratio can be determined directly from the observed intensity fluctuation decorrelation bandwidth B of a pulsar of known distance L: $\Delta n/\sqrt{a} \propto (BL)^{-1/2}$. B is a measure of the largest bandwidth over which intensity fluctuations remain correlated. Harris *et al.* (1970) estimate L from the observed dispersion measures n_eL and an assumed constant electron density $n_e = 0.06$ cm^{-3}, and find for 10 pulsars that $\Delta n/\sqrt{a}$ has an average value 1.9 cm^{-3} pc$^{-1/2}$ with 35 percent rms deviation. Note that $\Delta n/\sqrt{a}$ depends only on $L^{-1/2}$ and thus is rather insensitive to the assumed value of n_e. Lang (1971) also shows that a similar value, $\Delta n/\sqrt{a} = 1.65$ cm^{-3} pc$^{-1/2}$, is consistent with the pulsar data, while Rickett (1970) suggests $\Delta n/\sqrt{a} = 0.26$ cm^{-3} pc$^{-1/2}$ on the basis of other arguments. We adopt below the Harris *et al.* (1970) value since it leads to the greatest amount of scattering.

Substituting this value $\Delta n/\sqrt{a} = 1.9$ cm^{-3} pc$^{-1/2}$ into equation (1), we can estimate the size of the scattering angle for the OH source in W49 A as

$$\theta_{scat} = 7 \times 10^{-4} \text{ arc seconds}\,. \tag{2}$$

Since θ_{obs} for this source is about 100 times larger, we conclude that interstellar scattering plays no role in determining its apparent size. We note that Broderick (1971) reached this same conclusion independently. The scattering angles for some other sources are given in table 1; note that $\theta_{scat} \ll \theta_{obs}$ in all cases. The chief uncertainty is whether the value for $\Delta n/\sqrt{a}$ given by Harris *et al.* (1970) can be taken as characteristic of the entire galactic disk, or whether it is dependent upon our particular location. In any case, the only way that interstellar scattering would be able to account for the sizes of the W24 and W49 A maser sources would be if the value of $\Delta n/\sqrt{a}$ in other parts of the Galaxy nearer the sources were about 100 times greater than the value near us. There is no evidence that the interstellar medium is so different in other parts of the galaxy. Hence we conclude that the apparent correlation of θ_{obs} with distance is just a chance occurrence, or perhaps due to a selection effect related to source intensity. One might expect that larger sources would be intrinsically more luminous and hence visible to greater distances.

III. SCATTERING BY H II REGIONS

It has been suggested (Litvak 1971) that perhaps the observed sizes of astronomical masers are due to scattering within the H II regions often found associated with maser sources. We shall show that this scattering mechanism is also too small to account for the observed sizes.

First, we note that for scattering in the source vicinity, θ_{obs} will not in general be equal to the scattering angle θ_{scat}, as can be seen from figure 1. Here z_1 is the distance from the source to the scattering medium and z_2 is the distance from the scattering medium to the observer. In the limit of small angles, it is easy to show that

$$\theta_{obs} = \theta_{scat} \frac{z_1}{z_1 + z_2} . \tag{3}$$

If the scattering medium is taken to be an H II region adjacent to the source, one would expect z_1 to be no greater than 10 pc. In the case of W49 A, z_2 is 14 kpc, so that

$$\theta_{obs} = 7.1 \times 10^{-4} \theta_{scat} . \tag{4}$$

The maser radiation would be scattered most effectively by a high-density H II region known as an H II condensation (Wynn-Williams 1971; Schraml and Mezger 1969). The H II condensation associated with the small ($\theta_{obs} \approx 0''.05$) OH source in W49 A is not resolved observationally (Wynn-Williams 1971), but it is probably similar to the other condensations in W49 A, for which Wynn-Williams derives electron densities $\approx 8 \times 10^3$ cm^{-3} and sizes $L \approx 0.75$ pc. No data are available on the nature of the inhomogeneities in such a region; but if we assume for illustrative purposes that $\Delta n/n = 10^{-3}$ and $a = 10^{11}$ cm as is true in interstellar space (Rickett 1970), we obtain $0''.11$ for θ_{scat}, or a predicted value of $\theta_{obs} = 8.2 \times 10^{-5}$ arc seconds for the above condensation parameters. This is about 1000 times smaller than the actual observed size of the OH source. Although the assumptions made about the nature of the H II condensation were somewhat arbitrary, the factor of 1000 gives the argument a large margin of safety. Very large inhomogeneities on short distance scales would be required in order to account for the observed sizes. The geometric effect given by equation (3) is very general and places a strong constraint on any attempt to find a scattering mechanism which is confined to regions near the source.

The result that $\theta_{obs} \ll \theta_{scat}$ for scattering near the source is nearly independent of source geometry. It breaks down if a plane wave is emitted, as from a filamentary maser, but only if the divergence angle of the plane wave is less than θ_{scat} ($\sim 0''.1$), as can be seen from figure 1. Even in this unlikely case, scattering could not make the source appear larger than its actual size. The spatial extent of the plane wave front can be no greater than the size R of the source, so that scattering in the source vicinity cannot

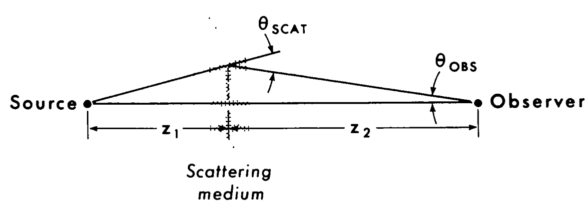

FIG. 1.—Scattering geometry showing relation between θ_{scat} and θ_{obs}

make θ_{obs} larger than $\theta_{max} = R/L$, and the apparent size $L\theta_{obs}$ is no greater than the true size for this case as well. For any source geometry, we would expect an inverse correlation between θ_{obs} and source distance if θ_{obs} were determined chiefly by scattering in the source vicinity. Such a correlation is not apparent in the currently available data.

A chance occurrence of an H II region along the line of sight yet not physically close to the masers (i.e., $z_1/z_2 \approx 1$) could scatter the radiation enough to account for the large sizes of W24 and W49 A. However, it seems unlikely that an H II region should happen to fall on the line of sight in two different instances; moreover, no such H II regions are indicated by hydrogen-recombination-line studies of W24 and W49 A (Weaver 1972).

IV. CONCLUSION

We have shown that scattering by fluctuations in the electron distribution does not appear to be responsible for the apparent sizes θ_{obs} of the interstellar OH masers, and our arguments apply as well to the H_2O sources, for which the scattering is two orders of magnitude weaker. We thus conclude that θ_{obs} gives a lower limit to the sizes of the sources.

In view of the difficulties presented by models in which θ_{obs} is very much smaller than the actual size of the masing region (Townes, Werner, and Evans 1972), it appears that a typical size for an OH maser is 10–1000 a.u., whereas a typical size for an H_2O maser is less than 10 a.u. (see table 1). If we accept the suggestion (Shklovskii 1966; Solomon 1968; Schraml and Mezger 1969) that these masers are protostars, we would expect to see a range of sizes indicating different stages of evolution of the protostars. In this model, we would expect that the more compact H_2O masers represent later stages of protostar evolution than do OH masers. The fact that the H_2O excitation energy is higher than the OH excitation energy is in agreement with this picture.

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